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In a proof-of-principle experiment frequencies between 6 and 21 GHz were generated with plasma densities in the $10^{12} cm^{-3}$ range and a capacitor period $2d=9.4cm$. The frequency spectra of these pulses are measured using a diffraction grating. Their relative spectral width is around 18%, the emitted frequency increases from 53 to 93 GHz when the capacitors are connected by pair to obtain a effective array period 4cm.

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FINAL TECHNICAL REPORT

A DC TO AC CONVERTER FOR RADIATION BASED ON A LASER
IONIZED CAPACITOR ARRAY
(Grant #F49620-95-1-0248)
(Period: April 1, 1995 – March 31, 1998)

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Accomplishments/New Findings:

Please see attached reprint –"Generation of microwave pulses from the static electric field of a capacitor array by an underdense, relativistic ionization front," P. Muggli et al., Phys. of Plasmas **5** (5) (1998) which summarizes all research performed under this grant.

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1. W. B. Mori, T. Katsouleas, J. M. Dawson, C. H. Lai, "Conversion of dc Fields in a Capacitor Array to Radiation by a Relativistic Ionization Front," Phys. Rev. Lett. **74**, 542 (1995).

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Interaction/Transitions:

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1. T. Katsouleas, C. H. Lai, P. Muggli, R. Liou, W. B. Mori, R. Brogle, C. Joshi, J. M. Dawson, "Tuneable Radiation Generation from a Laser-Ionized Gas-Filled Capacitor Array," 37th Annual Meeting, APS Division of Plasma Physics, Nov. 6-10, 1995, Louisville, KY.

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8. "Beam dynamics in plasma accelerators," T. Katsouleas, C. E. Clayton, K. Wharton, R. Kinter, T. Peters, S. Heifets, T. Raubenheimer, Workshop on Nonlinear and Collective Phenomena in Beam Physics, Italy, Sept. 1996.

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13. "Tunable microwaves from Cerenkov wakes in magnetized plasma," J. Yoshii, C. H. Lai, T. Katsouleas, W. B. Mori, and C. Joshi, 24th IEEE International Conference on Plasma Science, San Diego, CA, May 19-22, 1997.

14. "Radiation generation by an ionization front in a gas-filled capacitor array," P. Muggli, R. Liou, C. H. Lai, T. Katsouleas, C. Joshi, W. B. Mori, J. Dawson, 24th IEEE International Conference on Plasma Science, San Diego, CA, May 19-22, 1997.

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16. "Design for a 1GeV plasma-wakefield acceleration experiment at SLAC," T. Katsouleas, S. Lee, S. Chattopadhyay, W. Leemans, R. Assmann, P. Chen, F. J. Decker, R. Iverson, T. Kotseroglou, P. Raimondi, T. Raubenheimer, S. Rokni, R. H. Siemann, D. Walz, D. Whittum, C. Clayton, C. Joshi, K. Marsh, W. Mori, and G. Wang, 39th Annual Meeting, APS Division of Plasma Physics, Pittsburgh, PA, Nov. 17-21, 1997.

17. "Beam loading in hollow plasma channels," T. C. Chiou, T. Katsouleas and W. B. Mori, 39th Annual Meeting, APS Division of Plasma Physics, Pittsburgh, PA, Nov. 17-21, 1997.

18. "Excitation of the free streaming ($\omega=0$) mode by a moving ionization front," J. R. Hoffman, P. Muggli, T. Katsouleas, W. B. Mori, and C. Joshi, 39th Annual Meeting, APS Division of Plasma Physics, Pittsburgh, PA, Nov. 17-21, 1997.

19. "Generation of Radiation from a Static Electric Field by a Relativistic Ionization Front," Patrick Muggli, 39th Annual Meeting, APS Division of Plasma Physics, Pittsburgh, PA, Nov. 17-21, 1997.

20. "Novel DARC Sources," P. Muggli, J. Hoffman, R. Liou,C. Joshi, and T. Katsouleas,

21. 1998 IEEE ICOPS Meeting, Raleigh, NC June 1-5, 1998.

22. "Simulation and Experimental Results of the Excitation of the Free Streaming Mode in the Plasma Wake Created by a Moving Ionization Front," J. R. Hoffman, P. Muggli, T. Katsouleas, W. B. Mori and C. Joshi, 1998 IEEE ICOPS Meeting, Raleigh, NC June 1-5, 1998.

Generation of microwave pulses from the static electric field of a capacitor array by an underdense, relativistic ionization front*

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The dc to ac radiation converter is a new device in which a relativistic ionization front directly converts the static electric field of an array of alternatively biased capacitors into a pulse of tunable radiation. In a proof-of-principle experiment frequencies between 6 and 21 GHz were generated with plasma densities in the 10^{12} cm^{-3} range and a capacitor period $2d = 9.4$ cm. In the present experiment, short pulses with frequencies between 39 and 84 GHz are generated in a structure with $2d = 2$ cm. The frequency spectra of these pulses are measured using a diffraction grating. The spectra are discrete, and their center frequency varies linearly with the gas pressure prior to ionization (or plasma density), as expected from theory. Their relative spectral width is around 18%, consistent with the expected number of cycles (six) contained in the pulses. An upper limit of 750 psec (bandwidth detection limited) is placed on the pulses length. The emitted frequency increases from 53 to 93 GHz when the capacitors are connected by pair to obtain a effective array period of 4 cm. © *1998 American Institute of Physics.* [S1070-664X(98)92405-3]

I. INTRODUCTION

Two classes of radiation sources have proven to be extremely successful in producing high-power and/or high-frequency radiation. The first class uses emission from free electron beams to produce electromagnetic (EM) radiation from the microwave frequency range to the infrared (IR) (klystrons, gyrotrons, free electron lasers, masers,...) and even vacuum ultraviolet (VUV) (synchrotrons). The second class uses transitions between atomic or molecular states to produce EM radiation from IR to the VUV (lasers). Recently, alternate sources that directly convert static electric fields into EM radiation have been successfully tested in vacuum devices[1] and in photoswitched semiconductors.[2] In addition, laser-produced ionization fronts have been used to upshift the frequency of an existing radiation source[3] from 35 GHz to more than 150 GHz by a mechanism described as phase modulation in a time-varying medium,[4] or photon acceleration.[5]

In the new device,[6] the radiation is produced through conversion of the static ($\omega_0 = 0$) electric field from an array of alternatively biased capacitors of period $2d$ (wave number $k_0 = \pi/d$) by a laser-produced, underdense, relativistic ionization front. Each time the front crosses a capacitor it triggers a burst of current and, consequently, a burst of broadband radiation. The bursts from each capacitor sum coherently with a phase determined by the front velocity to produce an EM radiation pulse in the plasma with a particular frequency and propagation direction. Since the wave train

(ac) that exits the plasma is similar to the waveform of the static (dc) electric field, we refer to this device as a dc to ac Radiation Converter or DARC source. The energy carried by the EM pulse is taken from the electrostatic energy of the capacitor array. The laser pulse energy is used for the ionization of the working gas only. The frequency of the EM pulse is tunable by adjusting either the plasma density (i.e., the working gas pressure prior to ionization) or the capacitor spacing d. In principle, the pulse can be completely tailored for a specific application by modulating the distance between the capacitors along the array (frequency chirping), and by adjusting the voltage applied to each capacitor (temporal shape). The number of cycles of radiation is equal to half the number of capacitors in the array, and the device can produce very short (few cycles) EM pulses. By choosing the capacitor period d and the appropriate plasma density the device can be operated from the microwave to the IR or teraherz frequency range. Applications for a high-power, tunable, ultrashort pulse source ranges from advance radar and remote sensing to ultrafast chemical and biological imaging, ultrafast interaction in solids, atomic physics, etc.

Beside the EM mode excited in the plasma that is the main focus of this paper, a zero-frequency magnetic mode, the free-streaming or picket-fence mode, is theorized to be excited. This mode has never been observed experimentally, and should be observable in the DARC source. Also a small fraction of the energy is reflected at a very high-frequency ($\omega_R \cong 4\gamma_f^2 k_0 c$) since it experiences a double Doppler frequency upshift upon reflection off the relativistic ($\gamma_f > 1000$) ionization front.

This paper reviews the theory[6] (Sec. II) and the first experimental results[7] obtained with a DARC source with d

$x = v_f t$), a fourth plasma mode (labeled T_s in Fig. 2), called the free-streaming or picket-fence mode, is also excited. It consists of a static ($\omega_s = 0$) magnetic field, perpendicular to the capacitors electric field, with a direction alternating in space with the same periodicity $2d$ as the static electric field (see Fig. 1). This mode is sustained by the steady currents flowing between the capacitor plates. In the case where $\Delta \ll k_0$ the static electric field of the capacitor array can be expanded as[6]

$$E_y = \sum_{n=0}^{\infty} \frac{(-1)^n 2 k_0 V_0}{\pi \sinh([2n+1]k_0 b/2)} e^{i(2n+1)k_0 x}$$
$$\times \cosh([2n+1]k_0 y),$$

$$E_x = \sum_{n=0}^{\infty} \frac{i(-1)^n 2 k_0 V_0}{\pi \sinh([2n+1]k_0 b/2)} e^{i(2n+1)k_0 x} \qquad (3)$$
$$\times \sinh([2n+1]k_0 y),$$

where the origin is placed in the middle of one of the capacitors, and V_0 is the total voltage applied to the capacitors. Near the axis, the first term ($n=0$, amplitude E_0) in the sum is approximately equal to V_0/b, is always the largest by a factor 3 or more, and is the only one retained in the following analysis. To ensure the continuity of the fields everywhere along the boundary, all the modes are assumed to have the same spatial characteristics as the static field [Eq. (3)]. The sinh and cosh terms Fourier decompose into an infinite number of k_y components, and because of the dispersion relation for the transverse modes ($\omega^2 = \omega_{pe}^2 + k_x^2 c^2 + k_y^2 c^2$), each k_y component would lead to a different ω and k_x. However, for large upshift ($\omega_{pe} \gg k_0 c$) the $k_y^2 c^2$ term (of order $k_0^2 c^2$) in the dispersion relation can be neglected, and the transmitted mode can be considered as having a single frequency. To obtain the amplitudes of the fields for the five modes (R, T_1, T_2, T_3, T_s) the boundary conditions for the fields have to be solved in the front's frame and the results transformed back into the laboratory frame. For a large upshift ($\omega_{pe}/k_0 c \gg 1$) and a relativistic ionization front ($v_f \cong c$) they are approximated by

$$T_1 \cong 1 + 2(k_0 c/\omega_{pe})^2,$$

$$T_2 \cong -k_0 c/2\omega_{pe}(1 + 2k_0 c/\omega_{pe}),$$

$$T_3 \cong -k_0 c/2\omega_{pe} \times (1 + 2k_0 c/\omega_{pe}), \qquad (4)$$

$$T_s \cong -1,$$

$$R \cong (2\omega_{pe}/\gamma_f \beta_f k_0 c)^2.$$

Thus the amplitude of the electric field of the transmitted EM wave is approximately equal to that of the static electric field E_0 of the capacitors ($T_1 \cong 1$). Note that T_s is defined as cB_s/E_0. With an array of N capacitors the output pulse is $N/2$ cycles long, i.e., its time duration is $\tau = N\pi/\omega$, and its bandwidth scales as $\Delta\omega/\omega \approx 2/N$ and depends on the particular pulse shape. Assuming that the plasma completely shields the capacitors field, the energy carried by the output pulse is given by

$$W = \frac{1}{2} \sqrt{\frac{\varepsilon_0}{\mu_0}} \frac{N\pi A}{\omega} T_1^2 E_0^2, \qquad (5)$$

where A is the spot area of the ionizing laser pulse ($A \le a \times b$ the waveguide cross area). The output power is given by

$$P_{out} = \frac{W\omega}{N\pi} = \frac{1}{2} \sqrt{\frac{\varepsilon_0}{\mu_0}} A T_1^2 E_0^2. \qquad (6)$$

The efficiency of the device η, defined as the ratio of the energy in the output pulse to the electrostatic energy stored in the ionized volume, is given by

$$\eta = \frac{1}{2} \frac{k_0 c}{\omega} T_1^2. \qquad (7)$$

For large upshift ($\omega \gg k_0 c$, $T_1 \approx 1$), the efficiency tends toward $\eta \approx \lambda/d \approx 4k_0^2 c^2/\omega_p^2$. The energy of the laser pulse is not included in η. The above analysis is valid only for sharp fronts [i.e., front spatial extend much less than $(\gamma_f^2 k_0)^{-1}$]. A WKB analysis shows that the results for the transmitted mode remain the same for continuous fronts.[6] The sharpness of the ionization front depends on the ionizing laser pulse length and on the ionizing process.

III. EXPERIMENTAL RESULTS

A. Large structure

The large structure consists of $N = 12$ capacitors $a = 4.1$ cm wide with $b = 1.5$ cm, $d = 4.7$ cm, and the gap between capacitors is $\Delta = 0.6$ cm. The working gas is azulene ($C_8 H_{10}$, ionization potential 7.42 eV), and azulene vapor of a few millitorrs is obtained by sublimation of azulene crystals around 100 °C. Two photon ionization by a 50 psec, 30 mJ, 8 mm in diameter ultraviolet ($\lambda_L = 266$ nm) laser pulse yields to plasma densities in the 1×10^{11} to 5×10^{12} cm^{-3} range. For a fixed laser pulse intensity, the plasma density is expected to be linearly proportional to the initial azulene vapor pressure. The plasma density n_e is calibrated versus the azulene vapor pressure (for a fixed laser pulse intensity) by interferometry at 60 GHz in a Q-band waveguide vacuum system. The calibration is 5.1×10^{11} cm^{-3}/mT of azulene with 30 mJ of UV energy. A dc high voltage (HV) between 300 and 1000 V is applied to the capacitors. With these experimental parameters, Eq. (2) predicts that frequencies in the 10 GHz range should be produced. At these frequencies the capacitor array dimensions (a and b) are comparable to the wavelengths of the radiation generated ($\lambda \approx 3$ cm). The waveguide effect of the array can be taken into account in Eq. (2) [or Eq. (1)] by assuming that only one TE mode propagates in the structure:

$$\omega \cong \frac{k_0 v_f}{2} + \frac{\omega_{c,mn}^2}{2k_0 v_f} + \frac{\omega_{pe}^2}{2k_0 v_f}$$

$$\cong \frac{1}{2k_0 c}(k_0^2 c^2 + \omega_{c,mn}^2 + \omega_{pe}^2), \qquad (8)$$

where $\omega_{c,mn} = c[(n2\pi/a)^2 + (m2\pi/b)^2]^{1/2}$ is the cutoff frequency for the TE$_{mn}$ mode in the waveguide of transverse
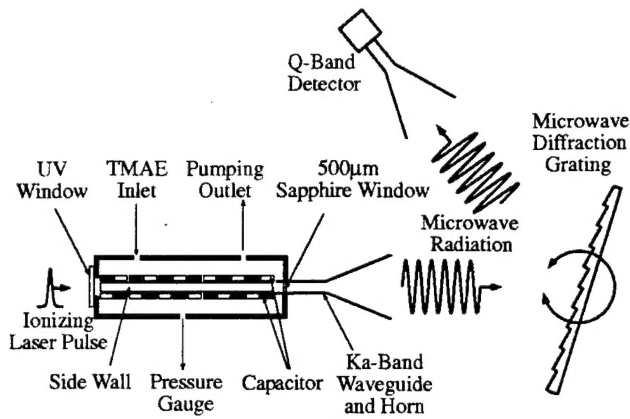
FIG. 6. Experimental setup for the frequency spectra measurements above 30 GHz. The angle between the emitting horn and the receiving horn is kept constant while the grating is rotated.
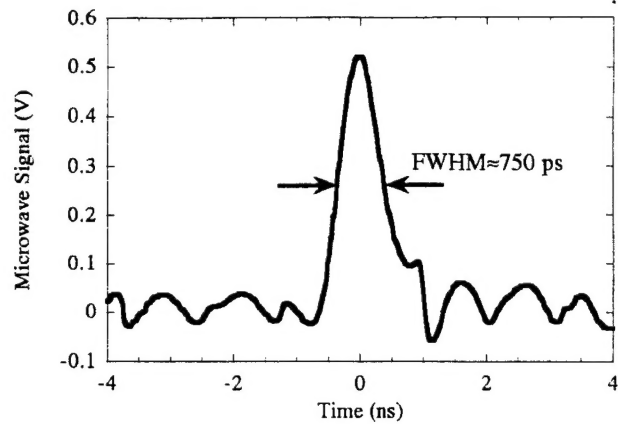

FIG. 7. The microwave signal detected by the microwave diode observed on a 1-GHz bandwidth oscilloscope. The FWHM is about 750 ps and is detection bandwidth limited. $P_{TMAE} = 14$ mT, $V_0 = 5.3$ kV, $f \cong 65$ GHz, $N = 12$; theory predicts that the pulse duration should be $\pi N/\omega \cong 93$ ps.

tion of the UV laser beam has been observed at pressures up to 1 Torr. The voltage the structure can withstand without breakdown decreases with increasing TMAE pressure and ultimately limits the frequencies [Eq. (8)] and powers ($\approx V_0^2$) reachable in this experiment. According to Eq. (8) frequencies above the Ka-band cutoff frequency (21.10 GHz) can be generated with plasma densities higher than $1.551.55 \times 10^{12}$ cm^{-3} (assuming propagation in the TE$_{10}$ rectangular mode). The frequency spectrum of the radiation generated with a given plasma density is measured using a microwave grating consisting of 50 6.64-mm grooves and blazed with a 30° angle. The incident wave is s-polarized and the signal is observed in the $m = -1$ or $m = -2$ reflection orders. For a grating with a blazing angle of 26°45', the reflection efficiency is strongly reduced[8] for $m\lambda/d < 0.7$, i.e., for frequencies larger than 64.5 GHz in the $m = -1$ order with a groove spacing of 6.64 mm. Thus in this experiment (blazing angle of 30°) frequencies above 60 GHz are observed in the $m = -2$ order. A waveguide and detection diode with the appropriate cutoff frequency are used to ensure that the signals observed at large incidence angle are really second-order reflections. The angle between the emitting and the receiving horn is kept constant (15°) while the grating is rotated to acquire the frequency spectrum (see Fig. 6). The microwave signal is detected using a DXP-22 millitech® diode (Q-band) and a 1 GHz bandwidth scope or digitizer connected to a computer-controlled data acquisition system. The spectrum is constructed from multiple shots taken at different angles of incidence on the grating. Cold test measurements with a Ka-band frequency sweeper show that the resolution of the frequency measurement system is 4 GHz between 26.5 and 40 GHz. This value is in agreement with the value obtained from the grating equation ($\partial f/\partial \theta$) times the equivalent horns/grating collection angle ($\Delta \theta \cong 6°$). The resolution can thus be calculated for larger incident frequencies for which no cold test is performed and is found to be around 12 GHz at 60 GHz. Note that observing higher frequencies in the $m = -2$ order preserves the good resolution ($\Delta f/f \leqslant 10\%$) measured up to 40 GHz.

Figure 7 shows the microwave signal when reflected from the back of the grating (acting as a plane mirror with a

7.5° incidence angle). The full width at half-maximum (FWHM) of the signal is 750 psec, and is bandwidth limited by the RC time constant of the microwave diode, cable, and oscilloscope ($\cong 1$ GHz bandwidth). At this TMAE pressure ($P_{TMAE} = 14$ mT), the pulse center frequency is expected to be about 65 GHz (see Fig. 10) with a pulsewidth of $\pi N/\omega \cong 93$ psec. (Similar signals were obtained over the whole frequency range of Fig. 10.) To our knowledge these are the shortest pulses in this frequency range.[9] Figure 8 shows the frequency spectrum of the radiation measured at TMAE pressures of 2, 5, and 24 mT, leading to center frequencies of 39 and 53, (observed in the $m = -1$ order), and 84 GHz (observed in the $m = -2$ order), respectively. These spectra are discrete and their relative spectral width $\Delta \omega/\omega$ defined as the ratio of the FWHM to their center frequency, together with the width of spectra obtained at 8 and 12 mT (not
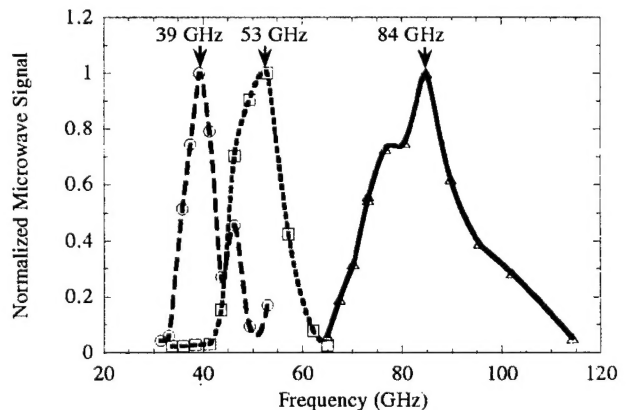

FIG. 8. Frequency spectra obtained at 2 mT (circles and long-dash line), 5 mT (squares and short-dash line), and 24 mT (triangles and continuous line) of TMAE pressure. The lines are added to guide the eyes. The spectra are obtained by observing the signal reflected in the $m = -1$ (2 and 5 mT) and $m = -2$ order (24 mT) of a microwave grating with 50 6.64-mm grooves blazed with a 30° angle. The spectra are normalized to their peak value. The center frequencies are 39, 53, and 84 GHz, and their respective FWHM are 7.0 GHz (18%), 10.9 GHz (20%), and 19.6 GHz (23%). The frequency resolution is about 4 GHz or 10% between 26 and 40 GHz both in the first and second reflection order.
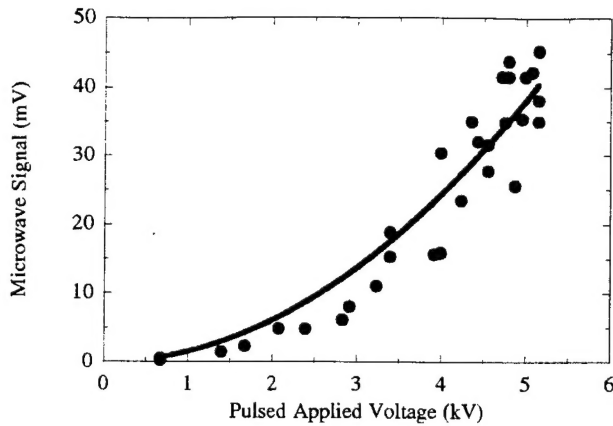
FIG. 12. Microwave signal as a function of the applied voltage V_0 at $P_{\text{TMAE}} = 15$ mT corresponding to a frequency of around 65 GHz. The line is the best fit to a $P \propto V_0^2$ dependency predicted by Eq. (6).

IV. OTHER DARC SOURCES

When operated in the microwave frequency range, the capacitor array has to act as a waveguide with acceptable transmission characteristics. The sources that were tested so far (see previous paragraph) exhibit relatively poor transmission characteristics in cold tests, which probably accounts for the relatively low power signals measured. The dc breaks of the capacitor array perturb the wall current necessary for the free propagation of the waveguide modes. These structures are essentially capacitor arrays supporting microwave propagation. In order to improve the microwave characteristics of the DARC source, and to take full advantage of the potential high output power of the scheme, a source in the X-band (Fig. 13) has been designed in which the capacitor plates are replaced by pins inserted in the waveguide through small hole in its narrow side wall. Cold test results indicate that the transmission characteristics of this device are those of a plain waveguide, except for stopbands created by the pins periodic structure. For example, the distance between the pins can be chosen such that the first stopband appears outside of the X-band frequency range (8.20–12.40 GHz). Calculations of the electric field pattern inside the waveguide show that the stored energy available for conversion into EM radiation is only a factor of 3 smaller than in the plate case. The output
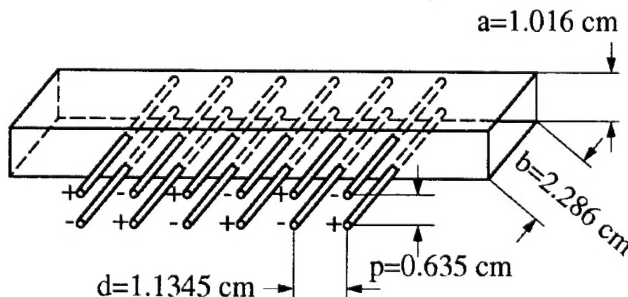

FIG. 13. Schematic of a DARC source in the X-band. The pins introduced through the narrow side wall of the waveguide play the role of capacitors. In cold test the structure exhibits no insertion, except for narrow stopbands created by the periodic pins.

power of this device should thus be much higher than that of the previous devices. This DARC source will be tested in the near future.

Equations (1) or (2) indicate that a DARC source with a period d of 330 μm produces teraherz radiation with plasma densities in the 10^{17} cm^{-3} range. Such a device has been built and will be operated in the 5–20 μm wavelength range. The plasma density required to produce those short wavelengths will be obtained through field ionization of nitrogen or xenon by a high-intensity femtosecond laser pulse.

V. SUMMARY AND CONCLUSIONS

The DARC source is a new device in which the static electric field of an array of alternatively biased capacitors is directly converted into EM radiation by a laser-produced relativistic ionization front. The results presented in this paper show that microwaves between 6 and 21 GHz and 39 and 93 GHz are produced with two devices with capacitor spacing in the centimeter range ($d = 4.7$ and 1.0 cm, period $2d$) and plasma densities in the 10^{12}–10^{13} cm^{-3} range. The radiation frequency can be tuned either by adjusting the plasma density (i.e., gas pressure prior to ionization) or the distance d between the capacitors. The pulses frequency spectra are discrete with a center frequency that varies linearly with the plasma density, and with a relative FWHM around 18%, consistent with their expected number of cycles ($N/2 = 6$, N is the number of capacitors in the array). The pulses are expected to be extremely short (<200 psec above 30 GHz, Ka-band source), and an upper bound to their width is experimentally placed at 750 psec (detection bandwidth limited). The amplitude of the measured signals follows the V_0^2 dependency (V_0 voltage applied to the capacitors) predicted by theory, but their power level remains lower than expected (in the 100 mW range up to $V_0 = 5$ kV). Cold test measurements show that the cut in the waveguide necessary for the capacitor array introduces an insertion loss of around -30 dB between 26.5 and 40 GHz (Ka-band) that certainly contributes to the low observed powers. Expression (6) is derive from a plane wave propagation theory. However, in the microwave frequency range the excitation and propagation of the generated radiation should take into account the characteristics of the supporting structure ("waveguide"). A new structure has been built in an X-band waveguide that exhibits no insertion loss between the narrow stopbands introduced by the periodic pins that act as capacitor plates. The issue of the power effectively produced by the DARC source and coupled to a waveguide mode will be better addressed with that structure. The range of frequencies generated by the DARC source will be extended to the terahertz range with a structure with a capacitor spacing of 330 μm and a plasma density around 10^{17} cm^{-3}. Experiments are conducted to detect the never observed free-streaming or picket-fence mode, a zero-frequency magnetic mode that is theoretically excited in the DARC source.